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Water movements in Lake Takanamiike, Niigata Prefecture, Japan

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ABSTRACT

A series of limnological experiments were carried out in Lake Takanamiike, a typical seepage lake, in order to clarify the mechanism of lake water movements, and the effects of wind shear stress and surface cooling on the movements were discussed. As results of a comparison between wind shear stress and surface cooling by the use of the velocity scale, the effect of surface cooling was larger than that of wind shear stress. The value of a coefficient of c_k^f, an indicator of the intensity of surface cooling on the vertical movements, was calculated at 0.37 to 0.42, and the figures were larger than those obtained in the previous studies. It is considered that the value changes with the lake scale and the strength of surface cooling.

KEY WORDS
water movement, wind shear, surface cooling
velocity scale, Lake Takanamiike

1 Introduction

Water movements in a natural lake depend upon various factors such as wind shear stress, heat balance, inflow and outflow of water. The strength and direction of water flow are also influenced by the shape of the lake basin, the depth, and so on. It is generally considered that a horizontal flow is chiefly caused by the wind shear stress, and that a vertical flow is induced by the thermal transfer such as surface cooling. As for wind, its duration is also one of the factors.

The effect of these factors on water movements remarkably changes by the thermal conditions of the lake. It is known that the wind shear stress is not exerted on the hypolimnion when the lake water is thermally stratified, and that the lake water is unstable when the water temperature is uniform to the lake bottom in winter. It has been certified that the lake water is easily mixed to the bottom in the observation of the thermal profile and water qualities such as dissolved oxygen and tritium. Sato (1986) showed that lake

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water was vertically mixed to a depth of 100 meters within a period of several hours in Lake Ikeda.

With reference to the horizontal movements of lake water, Arai (1985) observed the surface flow making use of floats in Lake Chuzenji, and Yokoyama (1994) made a similar observation in Lake Takanamiike and clarified the relationship between the wind velocity and the surface flow. Ohya (1993) showed the behaviors of the wind-drifted surface water, which was reflected in the distribution of water temperature.

In this study, the vertical movement is mainly considered. There are many studies on the vertical movements and mixing, especially in Lake Tahoe. Paerl *et al.* (1975) investigated the vertical mixing from the annual nitrate cycling, and made it clear that the lake was holomictic and that the lake water might have been completely mixed in the winter of 1972. Holm-Hansen *et al.* (1976) also showed that the water temperature and qualities had been homogenic in February of 1970. Furthermore, Imboden *et al.* (1977) discussed the lake water mixing by the use of tritium as a tracer and showed the new method of tritium measurements in order to elucidate the lake water mixing. They stated that there was essentially no variation in the profile of tritium concentration in August of 1973 and that the tritium profile gave a strong evidence for at least occasional complete mixing of Lake Tahoe.

Zeman and Tennekes (1977), in a theoretical and experimental analysis, showed the parametrization schemes applicable to the thermocline erosion in the ocean based on the study on the budget of turbulent kinetic energy at the atmospheric boundary layer. On the other hand, as to artificial reservoirs, Imberger *et al.* (1978) constructed a basic model for the dynamic consideration of medium size reservoirs. There are synthetic studies of the mixing in inland and coastal waters such as Fischer *et al.* (1979).

Sato (1986) investigated the relationship between the vertical mixing and the profiles of water temperature and water qualities such as dissolved oxygen in Lake Ikeda. It was concluded that the lake water was completely mixed to the bottom only in a severely cold winter which occurred at intervals of several years. Sato (1989) also examined the method of the expression of the wind shear stress and surface cooling in velocity scales. But it is not clearly proved whether the method is applicable to small lakes such as Lake Takanamiike or not.

The purpose of this study is to consider the effect of the wind shear strss and the surface cooling on the water movements in a small lake, furthermore to discuss the method of the expression of the moving factors in velocity scales. Lake Takanamiike has been selected as the experimental lake. It has a sufficient depth and hydrologically appropriate conditions.

2 Study area

Lake Takanamiike is located in a southwestern part of Niigata Prefecture in the central districts of Japan (Fig. 1). In this area, as snow falls to a depth of several meters every winter, the traffic is completely cut off and the lake is frozen over. The lake is covering an area of $0.032km^2$, and has a maximum depth of 14m and a volume of $2.1 \times 10^{-4}km^3$. The elevation of the lake surface is 535m. Its catchment area is $0.676km^2$ and to be covered by a luxuriant vegetation of conifers and broadleaves.

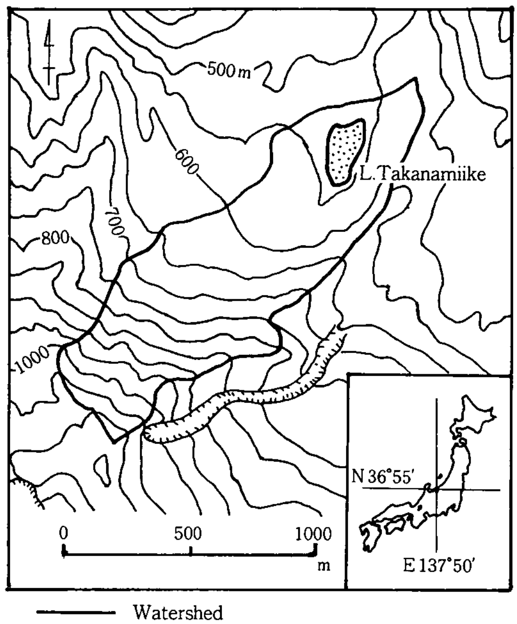

Fig. 1 Study area

The lake basin has a steep slope especially in the eastern part. Several small streams are observed in or after rain, but there is no perennial stream into the lake, which is mainly recharged by groundwater and temporary surface streams. The large catchment area spreads over the southwest of the lake, therefore a large amount of surface and groundwater seems to pour into the lake from the area. The lake has no outlet, so that, from the viewpoint of water balance, the outflow from the lake mainly consists of the groundwater and the evaporation from the lake surface. Thus, Lake Takanamiike is considered to be a seepage lake.

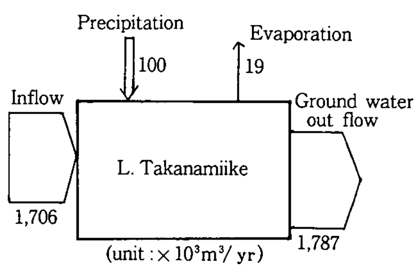

Fig. 2 Water balance of Lake Takanamiike (Sato *et al.*, 1992)

The water balance of Lake Takanamiike is schematically shown in Fig. 2. As the slope of the catchment area is steep, a rainfall to the area immediately drains into the lake except in winter when the precipitation to this area is almost snowfall and it is stored in the area until a thawing season begins. The maximum water level of the lake appears in April, and then the water level gradually decreases to the minimum in September. It is considered that the lake has been formed by the damming by land slides, and estimated from the experimental results on the bottom sediments that the lake is new and rapidly buried.

From the seasonal variation of lake water temperatures, the level of the thermocline in summer is the depth of about 1.5meters (Fig. 3), which is smaller than the value calculated from the fetch length. From the horizontal variations of surface water temperatures, Sato *et al.* (1992) showed that a lower temperature zone spread to the southern part of the lake and that it indicated the groundwater inflow.

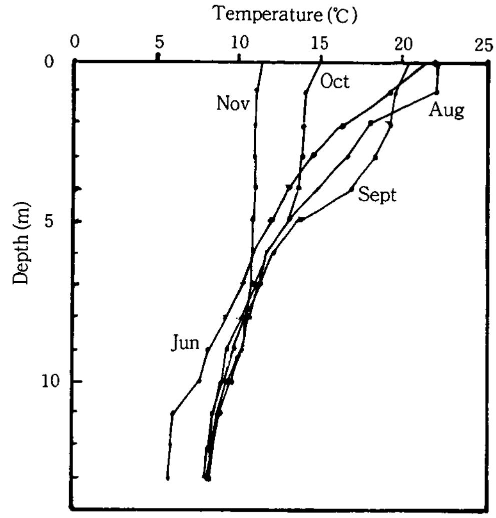

Fig. 3 Seasonal variation of the thermal profiles in Lake Takanamiike (Sato *et al.*, 1992)

On the qualities of lake water, the electrical conductivities varied from 110 to 130μS/cm in June to September in 1992, and those were about 100μS/cm in October to November. These lower values of electrical conductivity show that the residence time of water in the catchment area is short. The values of pH were around 8.4 in summer when the photosynthesis was active, in other seasons it indicated neutral values of around 7.0. There are some papers which have pointed out the water of Lake Takanamiike has a high calcium concentration, that is to be a gypsotrophic lake, affected by the surrounding lime stone formations (e.g. Fukuhara *et al.*, 1992).

The mean residence time calculated from the lake volume and the total inflow to the lake is about 0.12 years, in other words the lake water is renewed in a short time because of a lot of influx waters.

3 Horizontal movements of lake water

In Lake Takanamiike, there are a few studies on horizontal movements. Yokoyama (1994) clarified the velocities and the directions of the horizontal flows from the experiments making use of the original floats. The direction of surface flows was counterclockwise (Fig. 4), and the velocity of them was 1.6-3.3% of that of the wind velocity. The results agreed with the values obtained in other lakes. Ohya (1993) pointed out the higher tempera-

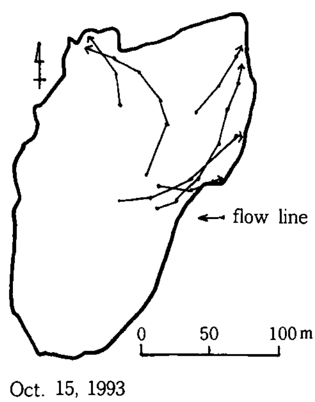

Fig. 4 Surface flow in Lake Takanamiike (Yokoyama, 1994)

ture zone appeared in the downwind side because of the drifted warm surface waters (Fig. 5).

Based on these results, it has been made clear that in Lake Takanamiike the horizontal movements of lake water mainly depend upon the wind shear stress, and that the velocity of the flow is related to that of the wind. Furthermore, the horizontal movements of lake water is closely related to the wind velocity if the wind velocity is high and the homothermy is thick. When the homothermy is thick, the wind shear stress is easily transferred toward the deep part, so that the direction of the horizontal flow in the deep part is similar to that of surface flow .

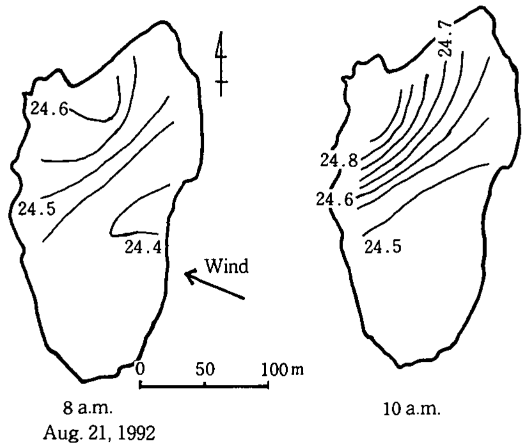

Fig. 5 Spatial distribution of surface water temperature (Ohya, 1993)

On the other hand, when the homothermy is thin and the thermal stratification is strong, the direction of surface flow is different from that of the deeper flow. The drifted surface water does not produce a remarkable vertical flow, and the occurrence of currents along the shore mostly cancels the difference in pressure. Although the influence of a lot of groundwater inflow appears in the distribution of the lake water temperature, it has not been able to catch the movements exactly by using of floats because of the small velocity of them.

4 Vertical movements of lake water

It is considered that the vertical movements of lake water are mostly caused by the surface cooling and the wind shear stress. These two factors are independent each other, but it is difficult to compare these factors directly. Thus, they are generally compared in terms of a velocity scale.

The velocity scale for surface cooling, u_f, is written as follows (Fischer *et al.*, 1979 ; Sato, 1989),

$$u_f = (-\alpha g h\, C_r / c_p \rho_0)^{1/3} \quad (1)$$

where g is the acceleration of gravity, h the thickness of mixed layer, C_r the surface cooling rate, c_p the specific heat of water at constant pressure, ρ_0 the density of water at the standard temperature, α the expansivity of water.

On the other hand, the wind shear stress, τ, is expressed as

$$\tau=c_d\rho_a u^2 \tag{2}$$

where u is the wind speed at the standard height, ρ_a the density of the air, c_d a drag coefficient. Then, the velocity scale for the wind shear stress, u_*, is expressed as follows,

$$u_* = (\tau/\rho_0)^{1/2} \tag{3}$$

and substituting Eq. (2) into (3) leads to

$$u_* = \{c_d(\rho_a/\rho_0)u^2\}^{1/2}. \tag{4}$$

It is practically known that the value of c_d ranges between 0.8×10^{-3} and 1.3×10^{-3} (Fischer *et al.*, 1979), and, in this study, it is given as 1.0×10^{-3}.

In Lake Takanamiike, the values of u_f were calculated at 0.34 to 0.48 from August 21 to October 26, 1992, and those of u_* were 0.11 to 0.23. Thus, it is considered that the surface cooling has more effect than the wind shear stress in the vertical movements of lake water. These results agree with the previous studies on larger lakes.

Based on the results above, the effect of the surface cooling to the vertical mixing of lake water is discussed. The energy balance for a column of lake water can be written as

$$dK/dt=-(dP/dt)-\rho_0\phi \tag{5}$$

where K is the turbulent kinetic energy, P the potential energy and ϕ the internal losses.

Considering the entrainment work for the lower water by the half of the depth of h, the following equation is obtained,

$$dP/dt=-\{\alpha g(h/2)(C_r/c_p)+\alpha g\Delta T\rho_0(h/2)(dh/dt) \tag{6}$$

where ΔT is the change of water temperature in the homothermy.

If it is assumed that the rate of the change of kinetic energy is proportional to the rate of surface cooling and the change of the homothermy thickness, the following equation is obtained,

$$dK/dt= (1/2)\{c_T{}^f\rho_0 u_f{}^2(dh/dt)\} \tag{7}$$

where $c_T{}^f$ is a coefficient to be practically determined. Substituting Eqs. (6) and (7) into Eq. (5),

$$(1/2)c_T{}^f \rho_0 u_f{}^2 (dh/dt) = (\alpha g (h/2)C_r/c_p\} - \alpha g \Delta T \rho_0 (h/2)(dh/dt) - \rho_0 \phi. \quad (8)$$

Rearranging Eq. (8),

$$(c_T{}^f u_f{}^2 + \alpha g \Delta Th)(dh/dt) = u_f{}^3 - 2\phi$$
$$= u_f{}^3 \{1-(2\phi/u_f{}^3)\} \quad (9)$$

and substituting $c_k{}^f$ for $1-(2\phi/u_f{}^3)$,

$$(c_T{}^f u_f{}^2 + \alpha g \Delta Th)(dh/dt) = c_k{}^f u_f{}^3 \quad (10)$$

where $c_k{}^f$ is a coefficient indicating the effect of surface cooling on the vertical movements of lake water.

According to the experimental data in Lake Takanamiike, the values of $c_k{}^f$ is calculated at 0.37 to 0.42. These values are larger than those given in the previous studies (Sherman et al., 1978 ; Sato, 1989).

5 Conclusions

Experimental data observed in Lake Takanamiike indicated that there existed wind drifted waters in the lake surface. And it can be considered that there is a large effect of wind on the horizontal movements of lake water. The drifted surface water does not produce a remarkable vertical flow, and the occurrence of currents along the shore mostly cancels the difference in pressure.

As regards the vertical movements, the influences of wind shear stress and surface cooling were compared, making use of the velocity scale. The values of u_f were 0.34 to 0.48, while those of u_* were 0.11 to 0.23, which indicated that the effect of surface cooling was larger than that of wind shear stress.

Furthermore, the coefficient of $c_k{}^f$, which indicated the intensity of the surface cooling on the vertical movements of lake water, was calculated at 0.37 to 0.42. These values are larger than those obtained in the previous studies. The coefficient of $c_k{}^f$ is considered to change with the lake scale and the strength of surface cooling.

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